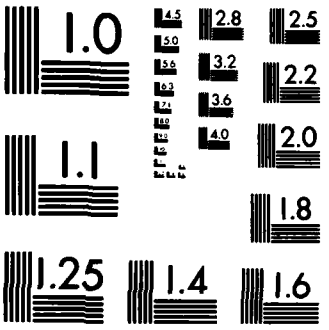
AD-A158 668 THEORETICAL MODEL OF HG(1-X)CD(X)TE PHOTOVOLTAIC AND PHOTOCONDUCTIVE INFR (U) AEROSPACE CORP EL SEGUNDO CA CHEMISTRY AND PHYSICS LAB A A FOTE 12 AUG 85 1/1

UNCLASSIFIED TR-0084A(5945-07)-1 SD-TR-85-53 F/G 17/5 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART

REPORT SD-TR-85-53

(2)

Theoretical Model of $Hg_{1-x}Cd_xTe$ Photovoltaic and Photoconductive Infrared Detectors

Prepared by

A. A. FOTE
Chemistry and Physics Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, CA 90245

12 August 1985

Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, CA 90009-2960

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-83-C-0084 with the Space Division, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by S. Feuerstein, Director, Chemistry and Physics Laboratory.

Lt Walter E. Leyland/YGJS was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) Program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Walter E Leyland

WALTER E. LEYLAND, Lt, USAF
MOIE Project Officer
SD/YGJS

Joseph Hess

JOSEPH HESS, GM-15
Director, AFSTC West Coast Office
AFSTC/WCO OL-AB

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A/1	

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SD-TR-85-53	2. GOVT ACCESSION NO. AD-A158 668	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THEORETICAL MODEL OF $Hg_{1-x}Cd_xTe$ PHOTOVOLTAIC AND PHOTOCONDUCTIVE INFRARED DETECTORS		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER TR-0084A(5945-07)-1
7. AUTHOR(s) Alfred A. Fote		8. CONTRACT OR GRANT NUMBER(s) F04701-83-C-0084
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space Division Los Angeles Air Force Station Los Angeles, Calif. 90009-2960		12. REPORT DATE 12 August 1985 13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

HgCdTe
Infrared detectors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Theoretical models have been developed for calculating the spectral responsivity and noise of $Hg_{1-x}Cd_xTe$ photovoltaic and photoconductive infrared detectors. These models are based on the classical theories for p-n junctions and sweepout-limited photoconductors. They incorporate numerous empirical expressions for describing all important material parameters of $Hg_{1-x}Cd_xTe$ as functions of the composition parameter x and

DD FORM 1473 (FACSIMILE)

Cont'd

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

temperature. The excess carrier lifetimes in n-type material are calculated by including radiative and Auger processes. In p-type material, Shockley-Read recombination is also included when appropriate. Provisions are made to include surface effects in photoconductors, but 1/f noise is neglected.

CONTENTS

I. INTRODUCTION

The detectivity of $Hg_{1-x}Cd_xTe$ detectors is controlled by composition and temperature, as well as by numerous other factors. To determine the optimum parameters required for a given application, a detailed theoretical model is essential. Such a model can also be employed to predict ultimate limits of detectivity. Finally, a sufficiently detailed model can help to establish whether the photoconductive or photovoltaic approach is best in a given situation.

To serve the above requirements, we have developed a computer model describing both photoconductive and photovoltaic $Hg_{1-x}Cd_xTe$ detectors. When equations for certain parameters, such as mobilities, were not available in the literature, semiempirical expressions were developed by fitting curves to published data.

This report provides a complete description of, and justification for, the various equations used in the model.

II. NOTATION

Many symbols are defined the first time they appear in the text. The following list includes those that are not:

- b thickness of the p-region, photovoltaic device
- D detector thickness
- d thickness of the n-region, photovoltaic device
- E_C conduction band energy
- E_V valence band energy
- h Planck's constant
- K Boltzmann's constant
- L distance between contacts (overlap structure in photoconductors)
- ℓ length of detector
- N_a concentration of acceptor atoms
- N_D concentration of donor atoms
- q electronic charge
- r reflection coefficient of detector front surface
- T temperature
- W detector width
- x composition parameter of $Hg_{1-x}Cd_xTe$
- V applied voltage
- Δf bandwidth of detector circuit

Subscripts

- N denotes n-type material
- P denotes p-type material

All equations are written in SI units. However, the results of sample calculations and the parameters used are expressed in the more common units appropriate to each.

III. MODEL EQUATIONS

A. ELECTRONIC PROPERTIES

For the energy gap, we use an expression recently developed by Hansen, Schmit, and Casselman (1982):

$$E_g = q[-0.302 + 1.93x + 5.35E\text{-}4(1 - 2x)T - 0.810x^2 + 0.832x^3] \qquad (1)$$

which is based on data covering 33 compositions from a variety of sources.

The effective mass of the electrons, expressed as

$$m_e^*/m_0 = 0.1E_g/q \qquad (\text{for } E_g/q < 0.2)$$

and

$$0.02 + 0.06(E_g/q - 0.2) \qquad (\text{for } E_g/q > 0.2) \qquad (2)$$

fits the measured and calculated values obtained from a number of sources (Dornhaus and Nimtz, 1976). The effective mass of the holes, on the other hand, appears to be constant and is generally taken as (Guldner et al., 1977)

$$m_h^*/m_0 = 0.55 \qquad (3)$$

The standard expression is used for the density of states in the valence band (Sze, 1969):

$$N_v = 2(2\pi m_h^* KT/h^2)^{3/2} \qquad (4)$$

Different procedures are used to calculate the intrinsic carrier concentration n_i and the Fermi energy E_F, depending on whether degenerate or nondegenerate conditions exist. In both cases, we make use of the Kane $\mathbf{k} \cdot \mathbf{p}$ solution to the band structure of HgCdTe, which takes into account the

nonparabolicity of the conduction bands. First we calculate the density of states in the conduction band from the following approximate equation, valid for the nondegenerate case (Bebb and Ratliff, 1971):

$$N_C = 4(4.83E21)(m_e^*/m_0)^{3/2}\ T^{3/2}$$

$$(1.0 + 3.75/\varepsilon + 3.28/\varepsilon^2 - 2.46/\varepsilon^3) \qquad (5)$$

where the factor of 4 arises from the four bands present in the case of (Hg,Cd)Te, which is a zincblende structure (Long and Schmit, 1970), and

$$\varepsilon = E_g/KT \qquad (6)$$

The intrinsic carrier concentration is then obtained from (Sze, 1969)

$$n_i^2 = N_C N_V \exp(-E_g/KT) \qquad (7)$$

The electron density N is (Sze, 1969)

$$N = 0.5\ [(N_D - N_A) + \sqrt{(N_D - N_A)^2 + 4N_I^2}] \qquad (8)$$

and the hole density P is (Sze, 1969)

$$P = n_I^2/N \qquad (9)$$

The position of the Fermi level with respect to the conduction band can then be calculated by means of (Sze, 1969)

$$\eta_F = (E_F - E_C)/KT = \ln(N/N_C) \qquad (10)$$

If η_F obtained is positive, we are dealing with degenerate statistics and η_F is reevaluated by means of the approximation

$$N = N_C\ (\eta_F + 1)^{3/2} \qquad (11)$$

Equation (11) is a good approximation of the exact theoretical solutions for degenerate, nonparabolic bands when $\varepsilon > 5$. Given η_F, the hole density is then

$$P = N_V \exp(-\eta_F - \varepsilon) \tag{12}$$

and

$$n_I^2 = N_C N_V \exp(-E_g/KT) \tag{13}$$

For the static dielectric constant, we use a linear fit to published data (Long and Schmit, 1970):

$$\varepsilon_s/\varepsilon_0 = 20 - 9.4x \tag{14}$$

The high-frequency dielectric constant is also composition-dependent (Reine et al., 1981) and is given by

$$\varepsilon_\infty/\varepsilon_0 = 9.5 + 8.14\ (0.6 - x) \tag{15}$$

For the photovoltaic devices, the built-in voltage V_{bi} is obtained by subtracting the value of η_F on the p-side from that on the n-side and multiplying by KT/q. We then calculate the width of the depletion layer by the standard expression for a two-sided abrupt junction,

$$W_D = \sqrt{(2\varepsilon_s/q)\ V_{bi}(N_N + P_p)/N_N P_p} \tag{16}$$

B. TRANSPORT PROPERTIES

An equation for the electron mobility was obtained by fitting a function to the data of Scott (1972). The two terms in the function are based on scattering by the lattice and by ionized impurities (of concentration $N_I = N_A + N_D$):

$$\mu_e^{-1} = 10^{-4}[E_g T^{3/2}/(8.08E6\ q) + x^4\ N_I T^{-3/2}/3.95E21] \tag{17}$$

Similarly, the equation below was fitted to published data for the hole mobility (Elliott et al., 1972; Tasch et al., 1970; Dennis et al., 1982):

$$\mu_h^{-1} = 10^{-4}(7.231E\text{-}7\ T^{3/2}/x + 9.084E\text{-}20\ N_I\ x^7\ T^{-3/2}) \quad (18)$$

The diffusion coefficients of the carriers are related to the mobilities by (Sze, 1969)

$$D = KT\mu/q \quad (19)$$

Finally, the ambipolar mobility and diffusion coefficient, required for the calculation of geometric effects in photoconductors, are, respectively (Sze, 1969),

$$\mu_a = \mu_e\mu_h\ |N - P|/\ (\mu_e N + \mu_h P) \quad (20)$$

and

$$D_a = D_e D_h\ (N + P)/(ND_e + PD_h) \quad (21)$$

C. CARRIER LIFETIMES

Properties of both the photoconductive and photovoltaic devices depend critically on carrier recombination lifetimes. Lifetime is determined by a combination of radiative, Auger, and Shockley-Read processes, expressed as

$$\tau^{-1} = \tau_R^{-1} + \tau_A^{-1} + \tau_{SR}^{-1} \quad (22)$$

For the radiative lifetime, we use a theoretical expression applicable for parabolic bands (Reine et al., 1981):

$$\tau_R^{-1} = B(N + P) \quad (23)$$

where

$$B = 2.26E19 \sqrt{\varepsilon_\infty/\varepsilon_0}\ (m_e^*/m_0 + m_h^*/m_0)^{-3/2}$$

$$(1 + m_0/m_e^* + m_0/m_h^*)\ (300/T)^{3/2}\ E_g^2 \qquad (24)$$

There are two important Auger processes, designated as Auger 1 and Auger 7, that affect carrier lifetime. The equations for these are (Grudzien et al., 1981)

$$(\tau_{A1})^{-1} = Aee(N + n_i^2/N)(N + Aehn_i^2/N)/n_i^2 \qquad \text{(for } \underline{p}\text{-type)}$$

$$(\tau_{A1})^{-1} = Aee(P + n_i^2/P)(n_i^2/P + AehP)/n_i^2 \qquad \text{(for } \underline{n}\text{-type)} \qquad (25)$$

and

$$(\tau_{A7})^{-1} = n_i^2/(6.11N^2)\ (\tau_{A1})^{-1} \qquad \text{(for } \underline{p}\text{-type)}$$

$$(\tau_{A7})^{-1} = P^2/(6.11n_i^2)\ (\tau_{A1})^{-1} \qquad \text{(for } \underline{n}\text{-type)} \qquad (26)$$

where

$$Aee = [2\ \tau_{Ai}(1 + Aeh)]^{-1}$$

$$Aeh = [\mu^{1/2}(1 + 2\mu)/(2 + \mu)]\ \exp[-(1 - \mu)E_g/((1 + \mu)KT)]$$

$$\mu = m_e^*/m_h^*$$

and τ_{Ai}, the Auger 1 lifetime in intrinsic material, is given by (Long and Schmit, 1970)

$$\tau_{Ai} = 3.8E\text{-}16(\varepsilon_s/\varepsilon_0)^2(E_g/KT)^{3/2}(m_0/m_e^*)\exp(E_g/KT) \qquad (26)$$

The Shockley-Read process, whereby recombination takes place with the assistance of energy levels inside the energy gap, appears to be avoidable in n-type (Hg,Cd)Te that is carefully grown. Thus we do not include that term in n-type calculations. This process has been difficult to eliminate in p-type material, however, and it is not clear at present whether or not it is avoidable by optimum crystal-growth techniques. When including it in our model of p-type material, we use the following expression for τ_{SR}:

$$\tau_{SR} = 2E14 \{P + N_V \exp[-(E_t - E_V)/KT]\}/(PN_A) \quad (27)$$

where

$$(E_t - E_V)/KT = (0.54 - 0.43E_g/q)\ (E_g/KT) \quad (28)$$

Equation (27) was derived as follows. The full expression for τ_{SR} is (Hannay, 1959):

$$\tau_{SR} = [\tau_{Po}(N + n_1) + \tau_{No}(P + p_1)]/(N + P) \quad (29)$$

where

$$n_1 = N_C \exp[(E_t - E_C)/KT) \quad (30)$$

$$_1 = N_V \exp[(E_V - E_t)/KT] \quad (31)$$

and τ_{Po} and τ_{No} are the lifetimes in the absence of ionized trap levels.

In the case of p-type HgCdTe, it reduces to

$$\tau_{SR} = (P + p_1)\ \tau_{No}/P$$

Low-temperature data, for which $\tau_{SR} = \tau_{No}$, indicate that τ_{No} is inversely proportional to the p-type doping level (Reine et al., 1981), an understandable result since, theoretically, τ_{No} is inversely proportional to the trap density, which might in turn be proportional to the Hg vacancy concentration. This gives the functional dependence exhibited in Eq. (27). The constant 2E14 was estimated by fitting to data from several sources (Reine et al., 1981; Bratt et al., 1981; Polla et al., 1981; Polla and Jones, n.d.).

The expression for the energy levels of the recombination centers, Eq. (28), was obtained by fitting to some data recently obtained by deep-level transient spectroscopy (DLTS) (Reine et al., 1981).

D. OPTICAL ABSORPTION AND QUANTUM EFFICIENCY

For the optical absorption coefficient, α, several expressions are employed, depending upon the value of the photon energy, E_λ, relative to the energy gap. Thus

$$\alpha = A \exp[3.495E22(E\lambda - E_g)/T] \qquad (\text{for } E_\lambda < E_g) \qquad (32)$$

and

$$\alpha = 3.75E10\ A\ (E_\lambda - E_g)^{1/2} \qquad (\text{for } E_\lambda > E_g + 0.5q) \qquad (33)$$

with

$$A = 5.6E5\ (m_e^*/m_0)^{1/2}$$

We derived these equations by fitting them to the available experimental data (Blue, 1964; Scott, 1969). For $E_\lambda - E_g$ between the ranges covered by those expressions, we use a cubic "splicing" function of the form

$$\alpha = r(E_\lambda - E_g)^3 + s(E_\lambda - E_g)^2 + t(E_\lambda - E_g) + u \qquad (34)$$

With this function, we can match the values of both the functions and their derivatives at the points of juncture.

Infrared detector arrays usually incorporate a combination passivant/insulator/antireflection coating. This introduces a wavelength-dependent factor that multiplies the detector responsivity. The factor is

$$\text{A/R factor} = (1 - r)(1 + 2\delta\cos\theta + \delta^2)/(1 + \delta)^2 \tag{35}$$

where

$$\theta = 4\pi nd/\lambda + \phi$$

r, δ, and ϕ are determined by the reflectivities and phase changes at the coating interfaces; d is the thickness; and n is the index of refraction of the coating.

We call the quantum efficiency, η, the number of free electronic carriers created for each photon that enters the material. For photoconductors, excluding reflections from the back surface of the detector, we have

$$\eta = 1 - \exp(-\alpha D) \tag{36}$$

In addition, we must know the gain factor, G, which establishes the likelihood that a photogenerated carrier will survive and travel sufficiently far to produce a signal in the measurement circuit. For photoconductors, the gain factor has recently been derived for the case of an asymmetric overlap structure with absorbing contacts (Fote, 1982), as proposed earlier (Kinch et al., 1979). For the simpler symmetric structure, the result reduces to

$$G_{PC} = [\tau V(\mu_e + \mu_h)/(\ell L)]$$

$$\{\ell/L + 2F(\alpha_2 - \mu_1)\sinh(\alpha_1 L/2)\sinh(\alpha_2 L/2)/[\alpha_1\alpha_2 L \sinh(\alpha_1 - \alpha_2)L/2]\} \tag{37}$$

where

$$\alpha_{1,2} = -\mu_a V/(2D_a L) \pm \sqrt{[\mu_a V/(2D_a L)]^2 + (D_a\tau)^{-1}} \tag{38}$$

$$F = \ell/L + (L/\mathscr{D}) \sum_{n=1}^{\infty} (-1)^n (K + K^{-1})^{-1} \sin(\pi n \ell/L)/(n\pi)^2 \qquad (39)$$

$$K = 2\pi n (L\mathscr{D}/4L_a^2) \left[(n\pi)^2 + (L/2L_a)^2\right]^{-1} \qquad (40)$$

$$\mathscr{D} = \mu_a \tau V/L \qquad (41)$$

$$L_a = (D_a \tau)^{-1} \qquad (42)$$

For photovoltaic detectors, ηG_{PV} consists of the sum of three terms, corresponding to contributions from the n, p, and depletion regions (Rogalski and Ruthowski, 1982):

$$\eta G_{PV} = (\eta G)_N + (\eta G)_P + (\eta G)_{DR}$$

These terms are

(1)
$$(\eta G)_N = [\alpha L_h^2/(1 - \alpha^2 L_h^2)]$$
$$\{\alpha e^{-\alpha d} - [(1 + \alpha K_N L_h) - e^{-\alpha d}(\cosh d/L_h + K_N \sinh d/L_h)]/$$
$$[L_h(\sinh d/L_h + K_N \cosh d/L_h)]\} \qquad (43)$$

(2)
$$(\eta G)_P = [\alpha L_e^2/(\alpha^2 L_e^2 - 1)]$$
$$\{\alpha e^{-\alpha(D-b)} - e^{-\alpha D}[(\alpha K_P L_e - 1) + e^{\alpha b}(\cosh b/L_e + K_P \sinh b/L_e)]/$$
$$[L_e(\sinh b/L_e + K_P \cosh b/L_e)]\} \qquad (44)$$

and

(3) $$(\eta G)_{DR} = e^{-\alpha d} - e^{-\alpha(D-b)} \tag{45}$$

with

$$K_N = D_h/(S_N L_h) = L_h/(S_N \tau_h)$$

$$K_P = D_e/(S_P L_e) = L_e/(S_P \tau_e)$$

$$L_e = (D_e \tau_e)^{1/2}, \text{ and } L_h = (D_h \tau_h)^{1/2}$$

where S_N and S_P are the surface recombination velocities at the two surfaces.

There remains one additional factor that must be included in the expression for the quantum efficiency/G product. Recall that for $E_\lambda < E_g$, we calculated α using Eq. (33). The absorption of radiation of this energy is due to the excitation of electrons into a band of energy levels that lie just below the conduction band (*Pankove*, 1971). The carriers in these particular states are immobile; they cannot travel to the depletion zone to produce a signal. However, a fraction of them can be thermally excited the rest of the way into the conduction band. The fraction that obtain mobility in this manner are determined by Boltzman statistics. Thus, in calculating G, we include the factor

$$\exp[(E_\lambda - E_g)/KT]$$

when $E_\lambda < E_g$. Without the presence of this factor, the model would predict a spectral responsivity that differs considerably from that actually measured.

E. NOISE MECHANISMS

The total current noise for the infrared detectors is obtained by quadratic addition of current noise from several sources. That is,

$$I_N^2 = \sum_i I_{Ni}^2 \tag{46}$$

The individual contributions are different in the cases of photoconductive and photovoltaic devices, and we discuss each separately. One noise type common to both, 1/f noise, is not included in our model for several reasons. First, 1/f noise is not sufficiently well understood that a reliable theoretical expression is readily available. Second, a reasonable expectation is that 1/f noise can be reduced to insignificance by proper fabrication techniques. Thus it should be excluded from models that seek to determine the ultimate sensitivity achievable in (Hg,Cd)Te detectors.

We first address the photoconductive detectors. Statistical fluctuations in the incoming photon flux are the first noise source, which translates into a noise signal in the detector described by (Long, 1977)

$$I_{PC,\phi}^2 = 4q^2 \eta \phi \ell W G_{PC}^2 \, \Delta f \tag{47}$$

The second source of noise in photoconductive devices arises from thermally driven generation-recombination processes, which in HgCdTe are expressed as (Long, 1977, 1967)

$$I_{GR}^2 = 4q^2 \, [NPLWD/(N + P)\tau] \, G_{PC_0}^2 \, \Delta f \tag{48}$$

where G_{PC_0} is obtained from the expression for G_{PC} by setting ℓ equal to L and F = 1, because the thermally generated carriers are produced throughout the volume of the device between the contacts, not merely in the window region as are the photo-induced carriers.

Finally, the photoconductors also exhibit Johnson noise:

$$I_J^2 = (4KT/R) \, \Delta f \tag{49}$$

Turning now to the photovoltaic detectors, we again have the noise associated with incoming photon flux, in this case given by (Long, 1977)

$$I_{PV,\phi}^2 = 2q^2\eta\phi\ell W G_{PV}^2 \, \Delta f \tag{50}$$

The expressions for the remaining noise currents in photovoltaic devices are based on the equation for shot noise, I_S^2, produced by a current I (Kingston, 1978):

$$I_S^2 = 2qI \, \Delta f \tag{51}$$

Each independently flowing current in the device generates shot noise. In particular, a device with zero net current will still exhibit shot noise if the device contains oppositely flowing microscopic currents that cancel one another on a macroscopic scale. Thus, the general expression for shot noise for a macroscopic current composed of oppositely flowing microscopic currents I_+ and I_- is

$$I_S^2 = 2q(|I_+| + |I_-|) \, \Delta f \tag{52}$$

The expression for the diffusion current in a photovoltaic device is

$$I_1 = I_D \, [\exp(qV/KT) - 1] \tag{53}$$

with

$$I_D = q[G_p N_p(\mu_e KT/q\tau_p)^{1/2} + G_N P_N(\mu_h KT/q\tau_N)^{1/2}]\ell W \tag{54}$$

If $G_N = G_P = 1.0$, the above equation reduces to the standard one for the diffusion current in a diode (Sze, 1969). The factors G_N and G_P depart from unity when electrical contact effects become significant in thin devices. In that case

$$G_P = [\cosh(b/L_e) + K_P\sinh(b/L_e)]/[\sinh(b/L_e) + K_P\cosh(b/L_e)] \quad (55)$$

and

$$G_N = [\cosh(d/L_h) + K_N\sinh(d/L_h)]/[\sinh(d/L_h) + K_N\cosh(d/L_h)] \quad (56)$$

The diffusion current produces a shot noise expressed by

$$I^2_{DF} = 2q[I_D + I_D \exp(qV/KT)]\ \Delta f \quad (57)$$

Thermal generation and recombination of carriers in the depletion region provide another source of current in p-n junctions. The associated current is (Sah et al., 1957)

$$I_2 = 2I_{GR} \sinh(qV/2KT)/[q(V_{bi} - V)/KT] \quad (58)$$

with

$$I_{GR} = q\ell W W_D[n_i + \alpha\phi \sqrt{\tau_N\tau_P}\, e^{-\alpha d}]/\sqrt{\tau_N\tau_P} \quad (59)$$

and gives a shot noise expressed by

$$I^2_{DPL} = 4q[I_{GR} + I_{GR} \sinh(qV/2KT)/(q(V_{bi} - V)/KT)]\ \Delta f \quad (60)$$

The presence of intergap energy levels caused by lattice defects and impurities can lead to a leakage current through the p-n junction. This trap-assisted tunneling current will, when present, provide another contribution to the shot noise. The current is given by

$$I_3 = I_T[\exp(qV/KT) - 1] \quad (61)$$

where

$$I_T = A\{1 - (E_g - E_t)/[q(V_{bi} - V]) + KT/[q(V_{bi} - V)]\}$$

$$\ln\{1 + B \exp[(E_g + qV - E_t - qV_{bi})/KT]/(1 + B)\}\ell W \qquad (62)$$

with

$$A = qN_T W_D P_1 \gamma_V N_C \omega_C / (n_1 \gamma_C + N_C \omega_C)$$

$$B = N_A \gamma_V / (N_C \omega_C + n_1 \gamma_C)$$

$$\lambda_V = (N_T \tau_{Po})^{-1}, \ \lambda_C = (N_T \tau_{No})^{-1}$$

$$N_C \omega_C = 1.63E15 \ m_e^* (V_{bi} - V) e^{-2\theta} / [W_D (E_G - E_t)]$$

$$\theta = 6.626E45 [W_D E_g^2 / (V_{bi} - V)]$$

$$[\pi/2 + \sin^{-1}(1 - 2E_t/E_g) + 2(1 - 2E_t/E_g) \sqrt{(E_t/E_g)(1 - E_t/E_g)}]$$

and we take the trap concentration equal to the acceptor concentration, i.e., $N_T = N_A$. This gives a tunneling noise current of

$$I_{Tun}^2 = 2qI_T[1 + \exp(qV/KT)] \ \Delta f \qquad (63)$$

F. DEVICE RESISTANCE

The resistance of the photoconductors is written

$$R = (L/qW) \ [\mu_e(ND + N_{ss}) + \mu_h PD]^{-1} \qquad (64)$$

an expression that allows us to include the effect of conduction through an accumulated surface layer with surface-state density N_{ss}.

For photovoltaic detectors, the parameter of greater interest is the

resistance-area product at zero bias, given by

$$(R_0A)^{-1} = A^{-1}\,(dI/dV)_{V=0} \tag{65}$$

where I is the total current through the device, including I_1, I_2, and I_3 [Eqs. (53), (58), and (61)].

G. RESPONSIVITY AND DETECTIVITY

The responsivity, in amperes per watt, to incoming radiation of wavelength λ, is given by

$$\mathscr{R}_\lambda = (\text{A/R factor})\ \eta G q\lambda/(hc) \tag{66}$$

where $G = G_{PC}$ or G_{PV}, depending upon the device type of interest.

In addition to knowing the responsivity of a detector to infrared radiation of a single wavelength, one would ocassionaly like to calculate the response to radiation from a black-body source of a given temperature. To do this, one needs to calculate an effective $\mathscr{R}$ by integrating over the wavelength band of interest. Thus

$$\mathscr{R}_{eff} = \int_{\lambda_1}^{\lambda_2} (\text{A/R factor})\ \mathscr{R}_\lambda dE_\lambda / \int_{\lambda_1}^{\lambda_2} dE_\lambda \tag{67}$$

For black-body radiation, dE_λ is given by

$$dE_\lambda = 3.73\text{E-}16(\text{area})\ \lambda^{-5}/(e^{B/\lambda T}-1)\ d\lambda \tag{68}$$

with B = 1.438E-2. The computer program includes provision for this integration to be performed numerically.

Finally, the normalized detectivity is defined as

$$D^* = (\mathscr{R}/I_N)(\ell W \Delta f)^{1/2} \tag{69}$$

REFERENCES

1. Abramowitz, M. and I. A. Stegun, Handbook of Mathematical Functions, (Dover Publications, Inc., New York, 1965).

2. Anderson, W. W., Infrared Phys. 20, (1980), 353.

3. Bebb, H. B. and C. R. Ratliff, J. Appl. Phys. 42 (1971), 3189.

4. Bratt, P. R., D. R. Rhiger, K. J. Riley, and J. Y. Wong, Technical Report 81-4063, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio (August 1981).

5. Dennis, P. N. J., C. T. Elliott, and C. L. Jones, Infrared Phys. 22 (1982), 167.

6. Dornhaus, R. and G. Nimtz, Solid-State Physics, Springer Tracts in Modern Physics, Vol. 78, G. Hohler, ed. (Springer-Verlag, New York, 1976).

7. Elliott, C. T., I. Melngailis, T. C. Harman, and A. G. Foyt, J. Phys. Chem. Solids 33 (1972), 1527.

8. Finkman, E. and Y. Nemirovsky, J. Appl. Phys. 50 (1979), 4356.

9. Fote, A. A., "Evaluation of Asymmetric Overlap Structure for Photoconductors," Infrared Phys. 22 (1982), 323.

10. Grudzien, M., K. Jozwikowski, J. Piotrowski, and H. Polakowski, Infrared Phys. 21 (1981), 201.

11. Guldner, Y., C. Rigauz, A. Mycielski, and Y. Cowder, Phys. Stat. Sol. 82 (1977), 149.

12. Hannay, N.B., Semiconductors, (Reinhold Publishing Corporation, New York, 1959).

13. Hansen, G. L., J. L. Schmit, and T. N. Casselman, J. Appl. Phys. 53 (1982), 7099.

14. Kinch, M. A., S. R. Borrello, B. H., Breazeale, and A. Simmons, Infrared Phys. 17 (1977), 137.

15. Kingston, R. H., Detection of Optical and Infrared Radiation, Springer Series in Optical Sciences, Vol. 10, D. L. MacAdam, ed. (Springer-Verlag, New York, 1978).

16. Long, D., Infrared Phys. 7 (1967), 169.

REFERENCES (Continued)

17. Long, D., Optical and Infrared Detectors, Topics in Applied Physics, Vol. 19, R. J. Keyes, ed. (Springer-Verlag, New York, 1977).

18. Long, D. and J. L. Schmit, chapter in Infrared Detectors, Semiconductors and Semimetals, Vol. 5, R. K. Willardson and A. C. Beer, eds. (Academic Press, New York, 1970).

19. Melngailis, I. and T. C. Harman, chapter in Infrared Detectors, Semiconductors and Semimetals, Vol. 5, R. K. Willardson and A. C. Beer, eds. (Academic Press, New York, 1970).

20. Pankove, J. I., Optical Processes in Semiconductors (Dover Publications, Inc., New York, 1971).

21. Polla, D. L. and C. E. Jones, "Deep-Level Transient Spectroscopy in $Hg_{1-x}Cd_xTe$" (submitted for publication).

22. Polla, D. L., J. F. Shanley, J. A. Mroczkowski, M. B. Reine, and R. L. Aggarwal, data presented at the United States Workshop on the Physics and Chemistry of Mercury Cadmium Telluride, Minnesota (28-30 October 1981).

23. Reine, M. B., A. K. Sood, and T. J. Tredwell, chapter in Mercury Cadmium Telluride, Semiconductors and Semimetals, Vol. 18, R. K. Willardson and A. C. Beer, eds. (Academic Press, New York, 1981).

24. Rogalski, A. and J. Ruthowski, Infrared Phys. 22 (1982), 199.

25. Sah, C.-T., R. N. Noyce, and W. Shockley, Proc. IRE 45 (1957), 1228.

26. Scott, M. W., J. Appl. Phys. 40 (1969), 4077.

27. Scott, W., J. Appl. Phys. 43 (1972), 1055.

28. Sze, S. M., Physics of Semiconductors. (Wiley-Interscience, New York, 1969).

29. Tasch, A. F. Jr., R. A. Chapman, and B. H. Breazeale, J. Appl. Phys. 41 (1970), 4202.

LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military space systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

Aerophysics Laboratory: Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, environmental hazards, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed laser development including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiation transport in rocket plumes, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photosensitive materials and detectors, atomic frequency standards, and environmental chemistry.

Computer Science Laboratory: Program verification, program translation, performance-sensitive system design, distributed architectures for spaceborne computers, fault-tolerant computer systems, artificial intelligence and microelectronics applications.

Electronics Research Laboratory: Microelectronics, GaAs low noise and power devices, semiconductor lasers, electromagnetic and optical propagation phenomena, quantum electronics, laser communications, lidar, and electro-optics; communication sciences, applied electronics, semiconductor crystal and device physics, radiometric imaging; millimeter wave, microwave technology, and RF systems research.

Materials Sciences Laboratory: Development of new materials: metal matrix composites, polymers, and new forms of carbon; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

Space Sciences Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.

END

FILMED

10-85

DTIC